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SPECIAL REVIEW EVIDENCE BASED CARDIOLOGY

# The basics of echocardiography

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**Abstract** Cardiac echocardiography is becoming an essential diagnostic tool for a variety of cardiac pathology. Acquiring the necessary knowledge will help non cardiac and the cardiac specialist to understand the echocardiography images and reports and in return will improve the care of the patients. The aim of these of publication is to address the basic knowledge of cardiac echocardiography and the recent advances of its applications.


## 1. Introduction

This series of publication in this issue and the upcoming issues will be aimed to address the basic knowledge of echocardiography and the recent advances of its application. This issue deals with:

1. Historical background of echocardiography.
2. Ultrasound production and detection.
3. The Piezoelectric effect.
4. Modes of image display.
5. How the ultrasound image is created.
6. Echocardiography topographic views.
7. From 2D imaging to real-time 3D imaging.

## 2. Historical background of echocardiography

Echocardiography (ECHO) – is the use of ultrasound to examine the heart. It is safe and non invasive technique. From the early days of Galen and Avicenna to Ibn al-Nafis and Leonardo da Vinci, there was a dream to image the beating heart. The concept of "seeing" structures using "sound" evolved in the 1920s, when ultrasound produced by piezoelectric crystals was used to detect flaws in metals. The collaboration between Edler and Hertz that began in Lund in 1953 started the development of medical ultrasonic's and using an industrial ultrasonic flaw detector, they obtained time-varying echoes transcutaneously from within the heart. The first clinical applications of M-mode echocardiography were concerned with the assessment of the mitral valve from the shapes of the corresponding waveforms. The diffusion of echocardiography into clinical practice depended on the availability of suitable equipment. The discovery of contrast echocardiography in the late 1960s further validated the technique and extended the range of applications. Two-dimensional echocardiography was first demonstrated in the late 1950s and the transesophageal echocardiography

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followed, in the late 1960s. It was, however, the demonstration by Bom in Rotterdam of real-time two-dimensional echocardiography using a linear transducer array that revolutionized and popularized the use of echocardiography. The development of the pulsed Doppler method in the late 1960s opened up new opportunities for clinical innovation. Technology has evolved over many years, and over the last few years a quantum leap was seen in the use of 3D echo application.

## 3. Ultrasound production and detection

Sound is disturbance travelling in a material-water, air body tissue or solid substance. Sound is characterized by its frequency, and its intensity. Frequency is measured in hertz (Hz) and its multiples (kHz, $10^3$ Hz and MHz, $10^6$ Hz). Sound of frequency higher than 20 kHz cannot be perceived by the human ear and is called Ultrasound. Echo uses ultrasounds of frequencies ranging from 1.5 to 7.5 MHz the nature of the material in which the sound travel in determine its velocity. The speed of sound in air is 330 m/s, while in the heart tissue, the velocity is 1540 m/s (Holmes, 1980).

## 4. The piezoelectric effect

Ultrasound results from the property of certain crystals to transform electrical oscillations into mechanical oscillations (sound) and vise versa. This phenomena is called the piezoelectric effect. Each transmitting and receiving period lasts about 1 ms.

At the core of each echo machine is this piezoelectric crystal transducer. When varying voltages applied to the crystals, it vibrate and transmits ultrasound. If the crystal is in the receiving mode, as it struck by ultrasound waves, it gets distorted. This in turn generate an electrical signal which is analyzed by the echo machine. Therefore the function of the crystal it emits a pulse and then listens for a reflection (Mason, 1950).

## 5. Characteristics of sound wave

Sound is a longitudinal mechanical wave that travels in straight line. All waves have the following characteristics: frequency, period, wavelength, propagation speed, amplitude and intensity (Edelman, 1997).

Frequency, period, amplitude and intensity are determined by the sound source. Propagation speed is determined by the medium, and wavelength is determined by both the source and medium.

*Frequency ($f$):* the frequency of a wave tells how many cycles occur in a second, it is measured in Hz and MHz. In medical ultrasound there is a tradeoff between penetration and resolution. Waves with high frequency have better resolution but less penetration and vice versa.

The period of a wave: is the time it takes for one complete cycle to occur. It is the reciprocal of frequency. Period is measured in seconds (s) or microseconds (μs). Period and frequency are reciprocals, i.e. Period in sec × Frequency in HZ = 1.

*Amplitude*: is the maximum height that occurs in a wave minus its average value. It is measured in watts (W) and microwatts (μW). Amplitude can be also expressed in Decibels. A decibel is the ratio of the final to the initial intensity of the sound wave.

*Intensity:* is a magnitude, such as energy or a force, divided by a unit of area, the amount of energy transferred measured in watts (W) divided by the area of the sound beam measured in square meters ($W/m^2$). Amplitude and intensity describe the strength of a sound beam.

*Wavelength ($\lambda$):* is the distance or space needed for one cycle to occur, it is measured in meters (m) and millimeters (mm). Wave length is inversely related to frequency, higher frequency waves have shorter wavelength.

*Propagation speed ($V$):* is the speed at which sound moves through a medium. It is measures as m/s or mm/μs.

$$V = f \times \lambda$$

where $V$ is the propagation velocity, $f$ is the frequency, and $\lambda$ is the wave length.

Hence for an ultrasound beam with a frequency $f$ of 3 MHz, the wavelength $\lambda$ is calculated as follows:

$$1.54 = 3 \times \lambda$$

$$\lambda = 1.54/3 = 0.51$$

## 6. Modes of image display

There are various known imaging ultrasound modes, the A-mode, B-mode, M-mode, real-time mode, pulsed wave Doppler, continuous wave Doppler and color Doppler (Otto, 2004; Feigenbaum, 1996).

*A-mode (amplitude-mode):* when the ultrasound beam encounters an anatomic boundary, the received sound impulse is processed to appear as a vertical reflection of a point. On the display, it looks like spikes of different heights (the amplitude). The intensity of the returning impulse determined the height of the vertical reflection and the time it took for the impulse to make the round trip would determine the space between verticals. The distance between these spikes can be measured accurately by dividing the speed of sound in tissue (1540 m/s) by half the sound travel time. A-mode ultrasound imaging is now obsolete in medical imaging.

*B-mode:* when the ultrasound signal is used to produce various points whose brightness depends on the amplitude instead of the spiking vertical movements in the A-mode. The vertical position of each bright dot is determined by the time delay from pulse transmission to return of the echo and the horizontal position by the location of the receiving transducer element.

Different types of displayed B-mode images are: two-dimensional (2D)-mode, gray scale and real-time mode.

*M-mode:* the M-mode (motion-mode) ultrasound is used for analyzing moving body parts commonly in cardiac and fetal cardiac imaging. The application of B-mode and a strip chart recorder allows visualization of the structures as a function of depth and time. The M-mode ultrasound transducer beam is stationary while the echoes from a moving reflector are received at varying times.

A single beam in an ultrasound scan is used to produce the one-dimensional M-mode picture, where movement of a structure such as a heart valve can be depicted in a wave-like manner. The high sampling frequency (up to 1000 pulses per second) is useful in assessing rates and motion, particularly in cardiac structures such as the various valves and the chamber walls.

## 7. How the ultrasonic image is created?

### 7.1. Two-dimensional imaging

An electric current can be produced in a ''continuous'' current form or a ''pulsed'' form where the current is on and then off in a periodic way.

To create an image transducer should have a firing time and a listening time. So it has an on/off time, on time for emission or firing and off time for listening, i.e. the transducer doesn't have to fire continuously but intermittently. Hence pulsed ultrasound waves are used for imaging not continuous waves (Bom et al., 1971).

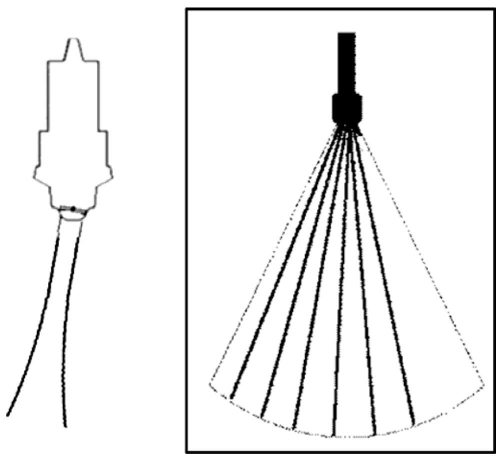


**Figure 1** Mechanical and electronically steering of the ultrasound beam.

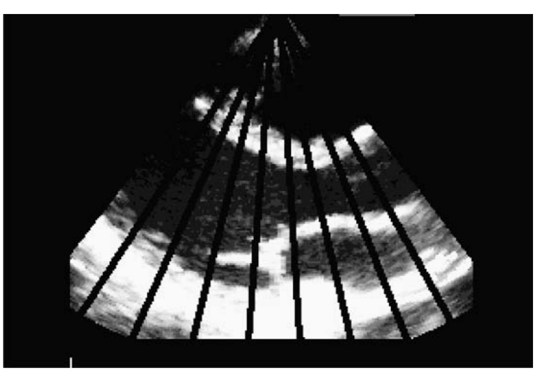


**Figure 2** Complete image generation from one ultrasound beam.

When a sound wave will travels through the body tissue until it travels forward till it hits a boundary of two different tissues. At this tissue interface, some of the sound wave will be reflected back and some will continue to travel through the next tissue. The sound waves that are reflected back create the echo which is picked up by the transducer and changed into an electric pulse. The electric pulse is then sent to the computer/display (Roelandt, 2000).

The computer or display calculates the time taken by the electrical pulse to make the round trip into the body and back and determines where on the display (depth) a dot is projected. The intensity of the reflected echo determines what shade of gray, from light to dark, it should be.

A two-dimensional image is built up by firing a beam vertically, waiting for the return echoes, all echoes along the beam are received, the picture along the beam is retained, and a new beam is sent out in the neighboring region. The ultrasound beam can be steered either mechanically or electronically (Fig. 1).

Maintaining the information from all the returned beams, one full sweep of the beam will then build up a complete image (Fig. 2).

With the current technology ultrasound machines can build up an image with sufficient depth and resolution of about 50 frames per second (FPS), which gives a good temporal resolution for 2D visualization of normal heart action.

### 7.2. Temporal resolution

It is the ability to accurately determine the position of an anatomic structure at a particular instant in time. The eye generally can only see 25 FPS (video frame rate), giving a temporal resolution of about 40 ms. Temporal resolution can be improved by increasing the sweep speed of the beam which is limited by the speed of sound, as the echo from the deepest part of the image has to return before the next pulse is sent out. If the desired depth is reduced, the time from sending to receiving the pulse is reduced, and the next pulse (for the next beam) can be sent out earlier, thus increasing sweep speed and frame rate.

Hence the frame rate is determined by sector size (width and depth) and line density (which affects lateral resolution).

### 7.3. Lateral resolution

Is the minimum distance that two side by side structures can be separated and still produce two distinct echoes. It depends on the beam width. The lateral resolution is approximately equals the beam diameter. Since the beam diameter varies with depth,

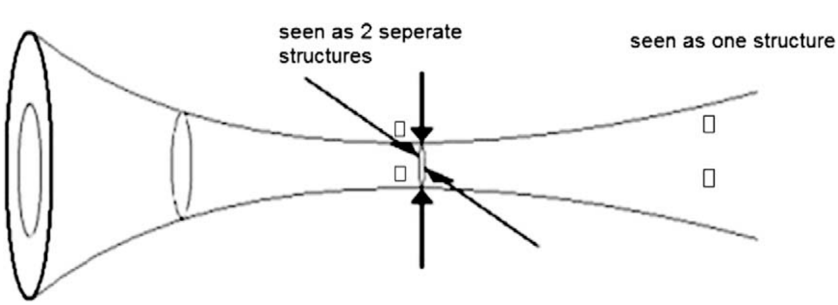



**Figure 3** Ultrasound beam variation with ultrasound depth.

the lateral resolution also varies with depth. It is best at near zone (focal) length (Fig. 3).

### 7.4. Longitudinal (axial) resolution

The ability to distinguish two structures that are close to each other front to back. It is determined by spatial pulse length. Shorter pulse (the result of high frequency and shortwave lens pulse) produces better images.

## 8. Echocardiographic tomographic views

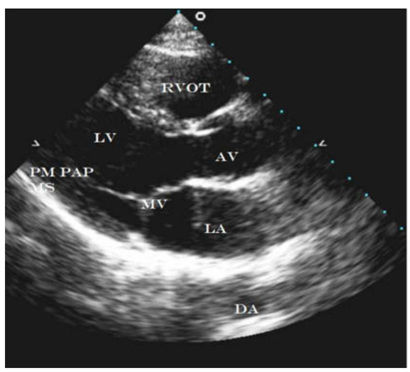
A detailed transthoracic echocardiographic examination involves imaging the heart from multiple windows. Each window is defined by the transducer position whether (parasternal, apical, subcostal, suprasternal) and the orientation of the tomographic plane through the heart (long axis, short axis, four-chamber, five-chamber) (Cerqueira et al., 2002). Several echocardiographic views are commonly used and these are:

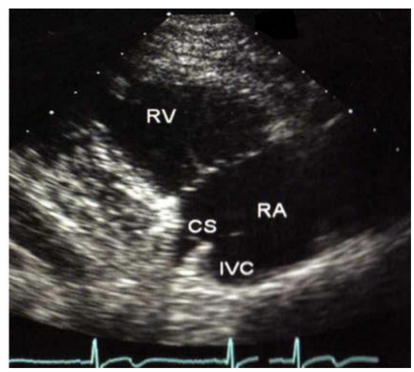
medial papillary muscle are commonly seen posterior to the plane of coaptation.

Posterior to the ascending aorta, is the left atrium. The right pulmonary artery can be seen superior to the left atrium as it crosses under the ascending aorta. The coronary sinus, usually less than 1 cm in diameter, may be seen immediately posterior to the mitral annulus. It can be distinguished from the descending thoracic aorta as the latter is external to the pericardium.

Posterior to the mid-left atrium, the descending thoracic aorta may be seen in cross-section.

Inferomedial angulation from the parasternal long-axis position allows viewing of right ventricular inflow which includes the right atrium, coronary sinus, posterior and anterior leaflets of the tricuspid valve and basal right ventricle. Superior angulation of the transducer permits visualization of the right ventricular outflow tract, including the pulmonary valve and main pulmonary artery (Cerqueira et al., 2002; Henry et al., 1980).



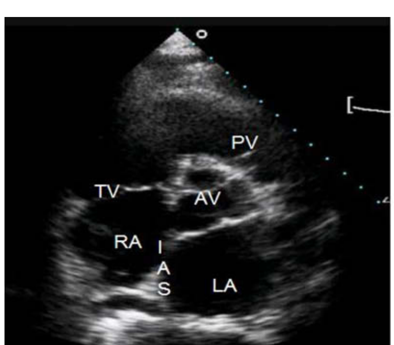

### 8.1. Parasternal long axis (PLAX)

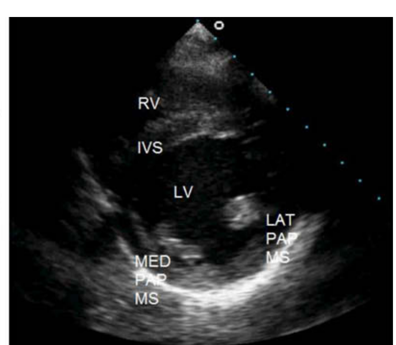
With the transducer in the 3rd or 4th left intercostal space, adjacent to the sternum, a long-axis view of the heart is obtained that bisects the aortic and mitral valve. The most anterior cardiac structure is the right ventricular outflow tract. The proximal structures of the ascending aorta (aortic root, sinotubular junction of the right and non-coronary sinuses), and the right (anterior) and non-coronary (posterior) cusps of the aortic valve can be visualized. The anterior and posterior mitral leaflets are also well delineated. Chordae from the posterior-

### 8.2. Parasternal short axis (PSAX)

This view can be obtained from the PLAX view by rotating the transducer a 70–110° clockwise rotations. With some superior to inferior tilt parasternal short axis (PSAX) views at the base (aortic valve), basal left ventricular (mitral valve), mid-left ventricular (papillary muscle), and apical left ventricular levels are obtained.

At the basal (aortic valve) level, both atria the interatrial septum, septal and anterior leaflets of the tricuspid valve, right ventricular free wall, right ventricular outflow tract, pulmon-



ary valve, and main pulmonary artery, can be seen "surrounding" the centrally positioned aortic valve. All three cusps of the aortic valve are identified, forming a "Y" configuration during ventricular diastole. The origins of the left and right coronary arteries may also be identified at approximately 3 o'clock and 10 o'clock, respectively.

Slight inferior angulation of the probe allows visualization of the left ventricle at the mitral valve level. The left ventricle appears like a doughnut. The mitral orifice has a characteristic ovoid or "fish-mouth" appearance. The right ventricle is also seen. Slightly more inferior angulation results in visualization of the contracting left ventricle at the papillary muscle level. The posterior and lateral papillary muscles are well appreciated. Further angulation of the transducer permits visualization of more apical segments of the left ventricle (Gardin et al., 2002).

### *8.3. Apical four-chamber*

With the patient in left lateral position, the transducer is placed on the apex. In this view, all four chambers of the heart are seen simultaneously. The left ventricle appears as a truncated ellipse, with the interventricular septum, apex, and lateral walls visualized. The lateral wall of the left ventricle is displayed to the right side of the screen. The basal, mid, and apical free wall of the right ventricle are seen on the left side of the screen, with the moderator band connecting the free wall to the septum. Inferiorly positioned on the screen are the left, right atria and the interatrial septum.

The pulmonary veins are seen at the bottom of the image sector superior to the left atrium. The anterior mitral leaflet appears medially, and posterior leaflet laterally. The septal and lateral tricuspid leaflets are also seen. The septal leaflet of the tricuspid valve is apically displaced relative to the mitral valve.

### *8.4. Apical five-chamber*

Anterior angulation and slight clockwise rotation of the transducer opens the aorta and give this view which allows visualization of the left ventricular outflow tract, right and left leaflets of the aortic valve, and proximal ascending aorta. Posterior angulation permits visualization of the coronary sinus and the posterior segment of the interventricular septum.

### *8.5. Apical two-chamber*

Rotation of the transducer counterclockwise from the apical four-chamber orientation gives the apical two-chamber view. In this orientation, the anterior, inferior, and apical walls of the left ventricle are visualized, along with the left atrium and its appendage.

### *8.6. Apical long axis*

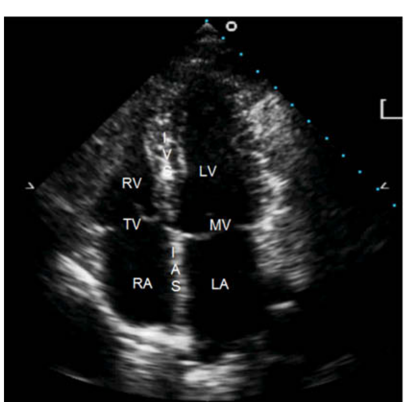
Further counterclockwise rotation and anterior angulation from the apical two-chamber allows the visualization of the apical long-axis view. In this view, the left ventricular outflow tract, anterior septum, aortic leaflets, and proximal ascending aorta are seen.

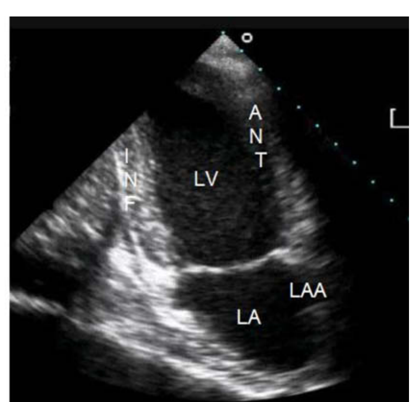
### *8.7. Subcostal four-chamber*

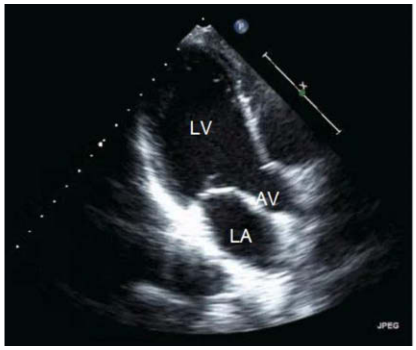
The subcostal views are obtained with the patient in supine position while the patient is taking a full inspiration to bring the heart as close as possible to the transducer and with the knees bent to relax the abdominal musculature. The transducer is positioned immediately below or to the right of the xiphoid process. This allows visualization of the right ventricle, the inferior interventricular septum, and anterolateral left ventricular walls. In this view the interatrial septum is oriented nearly perpendicular to the ultrasound beam. Thus, interrogation for an atrial septal defect is best from this position. Medial angulation of the transducer results in imaging of the hepatic veins and inferior vena cava as it enters the right atrium. Sliding the transducer to the left allows imaging of the abdominal aorta.

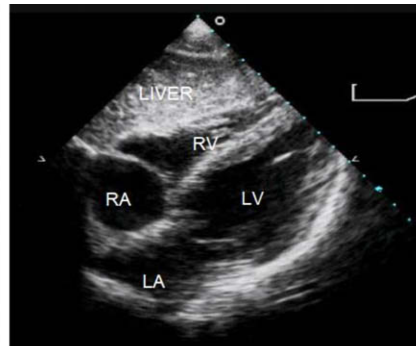
### *8.8. Suprasternal view*

With the patient supine and the neck extended, the transducer is placed in the suprasternal notch to obtain an image of the distal ascending aorta, aortic arch, and proximal descending aorta. The origin of the neck great vessels may also be appreciated. Below the lesser curvature of the aortic arch is a short-axis view of the right pulmonary artery (Henry et al., 1980; Gardin et al., 2002).





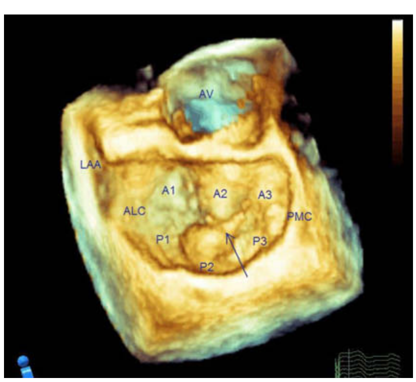




## 9. From 2D imaging to real-time 3D imaging

Mental reconstruction of the various 2D scanning planes as well as three-dimensional appreciation of cardiac anatomy is needed to integrate the echocardiographic information. Hence the need for real-time three-dimension echocardiography was growing. Microbeam former was a major breakthrough in technology that allowed communication of a huge number of piezoelectric elements (approximately 3000) in the phased-array transducer to the ultrasound system (Lange et al., 2001).

A phased-array transducer can steer a scan line in both the elevation and lateral dimensions. This allows a 3D set of data to be formed.

Current live 3D spatial imaging modes are: (a) *narrow angle acquisition:* a 3D volume sector that cannot span the entire heart. (b) *A Zoom mode in the narrow angle mode:* allows focusing in on a particular structure with high resolution with the tradeoff being a narrower data set. (c) *A full-volume acquisition:* that requires cardiac gating to acquire four cardiac cycles and then reconstruct them into an entire cardiac volume (some newer technologies uses single beat or two beats only). Multiplanar reconstruction slices can be taken from the 3D data set at any orientation. (d) *3D color Doppler-gated:* This adds color to full volume 3D acquisition.




Future advances in transducer and computer technology will allow wider angle acquisition and color flow imaging to be completed in a single cardiac cycle, which will shorten data acquisition and eliminate stitching artifacts. The transducers will have a smaller footprint and weight with higher spatial and temporal resolution (Wang et al., 2003; Lang et al., 2005).

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